Processing of metals with ps-laser pulses in the range between 10ps and 100ps

Marc Schmid[*a], Beat Neuenschwander[a], Valerio Romano[a], Beat Jaeggi[a] and Urs W. Hunziker[a]
[a]Bern Universtity of Applied Science, Pestalozzistrasse 20, CH-3400 Burgdorf, Switzerland

ABSTRACT

The potential of pulsed laser system in the range of 10ps to 100ps pulse duration for material processing has been further investigated. In detail the dependency of the volume ablation rate, penetration depth and threshold fluence on the pulse duration and number of pulses applied to the material will be discussed. The experimental results show that in the case of copper and steel, better results in quality and efficiency of the ablated material are achieved with shorter pulse durations.

Keywords: laser material processing, ultra short pulses, picosecond, ablation rate, penetration depth, threshold fluence

1. INTRODUCTION

In pulsed laser material processing two different types of laser systems with different regions of pulse durations are currently used. A first large family of pulsed laser systems are Q-switch laser systems which produce pulse durations in the region of nanoseconds. These types of lasers show high energy per pulse and are low cost systems working in the regime of hot ablation. Nevertheless for micro machining pulses with nanosecond pulse durations are less favourable as they show poor cutting, drilling and ablation quality on the microscopic level [1,2]. On the other hand much better performances in micro machining [1,2,3] are obtained by cold ablation with ultra short pulses of 10ps duration and less. For this kind of work industrial proved mode locked solid state lasers generating 10ps pulse duration are commercially available today. Shorter pulse durations down to femtoseconds are achieved by chirped pulse amplifications (CPA). Unfortunately these systems are in general cost intensive. Currently research is done on fibre based laser systems with Master-Oscillator Power-Amplification (MOPA) configurations. For such systems without CPA, pulse durations between 20ps and 100ps would allow to build even more cost effective systems. But this regime is hardly discussed in the literature. ~~t~~Therefore the aim of this paper is to report on micro-machining with laser pulses with pulse durations in the region of 10ps to 100ps. We will discuss our findings on ablation in copper (Cu-DHP) and stainless steel (1.4301).

2. THEORY

2.1 Threshold fluence and penetration depth

An extended discussion of the theory of cold ablation with femtoseconds and of hot ablation with nanoseconds can be found in [3,4,5]. The two important parameters for describing the ablation process in material are the threshold fluence Φ_{th} and the penetration depth δ. The threshold fluence Φ_{th} is a material parameter and describes the minimum energy per area which is needed to heat, melt and finally vaporize the bulk material. The penetration depth δ is a material parameter, as well, and describes the ability of the energy to penetrate into the material. In the case of ultra-short pulses, where the pulse duration is much shorter than thermalization time, the ablation depth z_{abl} per pulse is given by [2,3]:

$$z_{abl} = \delta \cdot \ln\left(\Phi / \Phi_{th}\right). \qquad (1)$$

The ablation depth z_{abl} is the depth up to which the material is removed. The equation (1) shows the well known logarithmic relationship between the ablation depth z_{abl}, the threshold fluence Φ_{th} and the initial fluence Φ and is a consequence of the two-temperature-model as discuss in length in [2,3,4,5]. In the case of cold ablation in the region of femtoseconds two regimes can be observed: For low fluence per pulse the penetration depth corresponds to the optical penetration depth into the material. The second regime, where the fluence is higher, the logarithmic relationship between

[*]Corresponding Author, marc.schmid@bfh.ch

the ablation depth and the fluence is still suitable but the penetration depth becomes the thermal penetration depth of the free electrons and is related to the thermalizing time of the electron; its value is higher than the optical penetration depth [3].

Additionally, in material ablation several pulses are applied to the same spot. Each pulse induses defects into the material. These defects are accumulated from pulse to pulse and as a consequence each following pulse sees a different condition. Therefore it is expected that the two material parameters Φ_{th} and δ depend on the number of pulses applied to the material (incubation effect). According to [6,7] the relation between the threshold fluence Φ_{th} and the number of pulses N for cold ablation can be written as:

$$\Phi_{th}(N) = \Phi_{th,1} \cdot N^{S-1} \quad (0 < S \leq 1), \tag{2}$$

where $\Phi_{th}(N)$ is the threshold fluence per pulse when applying N pulses, $\Phi_{th}(1)$ is the threshold fluence when applying one pulse and S is the accumulation factor with values between 0 and 1 for softening and above 1 for hardening the material, respectively; if S is equal to 1, no incubation will appear [6]. According to the equation (2) the threshold fluence per pulse decreases with increasing number of pulses N. But it has to be pointed out that the equation (2) predicts for an infinitive number of pulses that the threshold fluence per pulse becomes zero. From a physically point of view this is not possible.

2.2 Volume ablation rate

Even though the more pulses mean smaller threshold fluence per pulse as mentioned above, more pulses mean that more time for ablation is needed, too. Therefore for industrial applications the ablated volume ablation rate, defined as the volume V_{abl} of the ablated material per unit time t, is relevant as this parameter scales the ablation process efficiency. Therefore assuming an ideal Gaussian beam with an $M^2=1$ and with a given penetration depth δ and threshold fluence Φ_{th} the expression for the volume ablation rate dV_{abl}/dt as a function of the repetition rate f and the average power P_{av} is given by [8,9]

$$\frac{dV_{abl}}{dt} = \frac{1}{4} \cdot \pi \cdot w_0^2 \cdot \delta \cdot f \cdot \ln^2\left(\frac{2 \cdot P_{av}}{P_{av,th}}\right), \tag{3}$$

where $P_{av,th}$ is the average threshold power. It is defined as

$$P_{av,th} = f \cdot \pi \cdot w_0^2 \cdot \Phi_{th}, \tag{4}$$

where w_0 is the laser beam radius. The equation (3) mainly reflects the logarithmic relationship of the equation (1). Analyzing the equation (3) it can be seen that there is a maximum ablation rate

$$\left(\frac{dV_{abl}}{dt}\right)_{\max} = \frac{2}{e^2} \cdot \frac{\delta}{\Phi_{th}} \cdot P_{av} \tag{5}$$

at an optimum repetition rate

$$f_{opt} = \frac{2}{e^2} \cdot \frac{1}{\pi \cdot w_0^2 \cdot \Phi_{th}} \cdot P_{av} \tag{6}$$

According to the equations (5) and (6) the maximum volume ablation rate and the optimum frequency are proportional to the average power P_{av}. Dividing the equation (5) and (6) by the average power P_{av}, these two equations can be rewritten as:

$$\left(\frac{dV_{abl}}{dt}\right)_{\max} \cdot \frac{1}{P_{av}} = \frac{2}{e^2} \cdot \frac{\delta}{\Phi_{th}} \tag{7}$$

and

$$\frac{f_{opt}}{P_{av}} = \frac{2}{e^2} \cdot \frac{1}{\pi \cdot w_0^2 \cdot \Phi_{th}} \tag{8a}$$

or

$$\frac{f_{opt}}{P_{av}} = \frac{2}{e^2} \cdot \frac{1}{E_{th}}, \tag{8b}$$

respectively, whereas $\pi \bullet w_0^2 \bullet \Phi_{th}$ (equation 8a) is the threshold energy per pulse E_{th} (equation 8b). Therefore the maximum ablated volume per unit time per unit power and the optimum frequency per unit power are proportional to the two material parameter penetration depth δ and threshold fluence Φ_{th}. The maximum volume ablation rate and the optimum frequency decrease with decreasing penetration depth and increasing threshold fluence, respectively. A similar approach to volume ablation rate is described by G. Raciukaitis et al. [6], where the maximum volume ablation rate as a function of the beam waist and average laser power was investigated.

In the case of hot ablation, a dependency between the pulse duration, the threshold fluence and the penetration depth is known. Also it is rather a complicated relationship, it can be said that in general the threshold fluence and the penetration depth are proportional to the square root of the pulse duration.

Assuming that the dependency of the volume ablation rate on the penetration depth and the threshold fluence, respectively, for cold ablation as expressed in equation (3) is suitable for picoseconds as well, it is of interest to investigate the dependency of the two material parameters penetration depth δ and threshold fluence Φ_{th}, on the pulse duration and the number of pulses applied to the material.

3. EXPERIMENTAL SETUP

As a laser source a DUETTO ps-laser system of the company Time Bandwidth Productions AG was used. This laser generates laser pulses of 10ps pulse duration at the wavelength of 1064nm with energy per pulse up to 200µJ. With the help of etalons the pulse duration has been expanded to 20ps, 30ps, 50ps and 100ps. The repetition rate could be varied between 50 kHz and 1 MHz. A picker was incorporated in the set-up in order to be able to reduce the repetition rate down to single pulses. If not stated otherwise a repetition rate of 50Hz was chosen. This guaranteed that no heat or energy could be accumulated in the material, respectively.

To determine the penetration depth δ and the threshold fluence Φ_{th} several pulses were fired on the same spot ablating a crater. The ablation depth z_{abl} directly corresponds to the measured depth of the ablated crater. The threshold fluence can be calculated using equation (1). Alternatively the area of the ablated crater was measured and the threshold fluence can be calculated using the relationship according to [10] between the diameter of the crater area and threshold fluence. Both methods produced comparable results. The depth and the area of the crater were measured by taking pictures from the ablated crater with a Laser Scanning Microscope (LSM) and analyzing them with professional image processing software.

In order to estimate the volume ablation rate dV_{abl}/dt several lines were ablated at a fixed average power, repetition rate and pulse duration but at different scanner speed $v_{scanner}$. Afterwards the volumes of the ablated lines dV_{line} were measured using the LSM. Together with the scanner speed and the repetition rate the volume ablation rate per line dV_{line}/dt was calculated. The estimated volume ablation rate dV_{abl}/dt is the average of the volume ablation rate per line dV_{line}/dt for different scanner speed $v_{scanner}$.

As target material copper Cu-DHP and stainless steel 1.4301 have been taken.

4. EXPERIMENTAL RESULTS AND DISCUSSION

4.1 Dependency of threshold fluence and penetration depth on the number of pulses

In a first experiment the relationship between the threshold fluence Φ_{th} and the number of pulses N for copper and steel has been investigated. In order to calculate the threshold fluence Φ_{th} per pulse depending on the number of pulses the ablation depth z_{abl} on the target have been measured for different number of pulses N and different initial fluence Φ

applied with these pulses. Figure 1a) and 1b) show the threshold fluence for copper and steel as a function of the number of pulses for pulse durations of 10ps (diamond), 20ps (triangle), 30ps (square) and 50ps (dot), respectively. It is clearly seen that the threshold fluence Φ_{th} per pulse decreases with increasing number of pulses N as it is predicted by the equation (2).

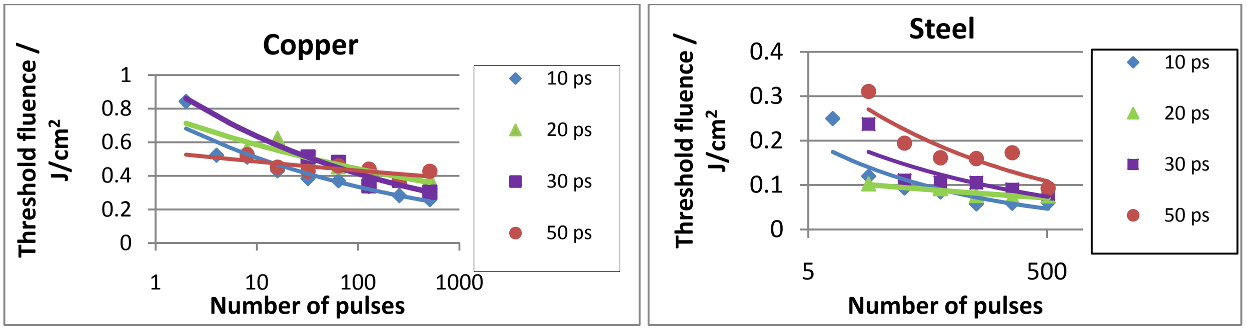


Figure 1a): Threshold fluence as a function of number of pulses; the material is copper. Figure 1b): Threshold fluence as a function of number of pulses; the material is steel.

Additionally, the measured points where fitted using expression (2) and the accumulation factor S was estimated. The value of the accumulation factor for copper is about 0.6-0.65 and does not change much for different pulse durations. In opposite to that the accumulation factor for steel varies from 0.9 for 20ps down to 0.7 for 50ps pulse duration. Therefore longer pulse durations induce more defects in steel. As mentioned above according to the equation (2) for infinitive number of pulses the threshold fluence per pulse decreases to zero whereas the experimental results suggest an approximation to a limit value greater than zero.

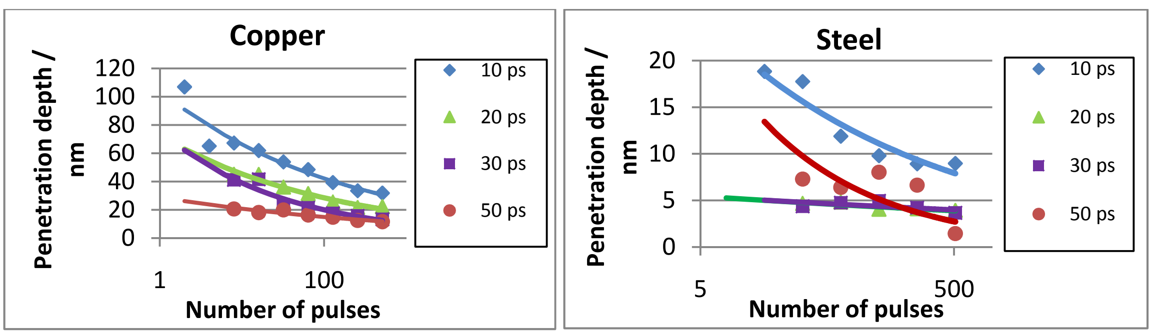


Figure 2a): Penetration depth in copper as a function of the number of pulse. Figure 2b): Penetration depth in steel as a function of the number of pulse.

A similar picture shows the penetration depth as a function of the number of pulses. In both cases, copper (figure 2a) and steel (figure 2b), the penetration depth decreases with the increasing number of pulses. The decreasing of the threshold fluence and penetration depth with increasing number of pulse can be explained with material transformation. From pulse to pulse the material is heated or even melted and cooled down again, which causes changes in the microstructure of the material. Secondly the threshold is influenced by the reflectivity of the material. Due to the changes of the roughness of the surface from pulse to pulse the reflectivity changes as well and therefore the threshold per pulse decreases.

4.2 Dependency of threshold fluence and penetration depth on the pulse duration

Further the dependency on the pulse duration has been investigated. Figures 3a) and 3b) show the dependency of the penetration depth and the threshold fluence on the pulse duration for copper and steel, respectively. In the case of copper the threshold fluence increases and the penetration depth decreases significantly with increasing pulse duration. For example the value of the penetration depth at 10ps (35.6 nm) is roughly three times as high compared to the value for 50ps (12.4 nm). In the case of steel the relationship between the pulse duration and the penetration depth and threshold value for low number of pulses is not that clear. Nevertheless it can be said that for a reasonable number of pulses (higher than 100 pulses) the penetration depth decreases and the threshold fluence increases with increasing pulse duration in the same scale as for copper. This indicates that the ablation process in the region of tenth of picoseconds is not cold. It rather shows a behavior similar to hot ablation, where the threshold fluence is proportional to the square root of the pulse duration.

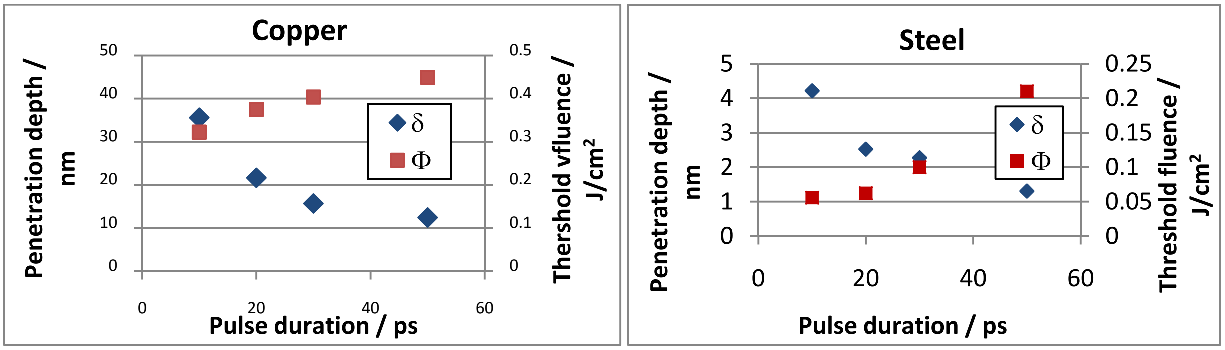


Figure 3a): Threshold fluence and penetration depth in copper as a function of the pulse duration. Figure 3b): Threshold fluence and penetration depth in steel as a function of the pulse duration.

This finding is not expected. Also the threshold fluence might be explained due to surface effects and changing reflectivity, the decreasing of the penetration depth with increasing pulse duration is difficult to explain. According to [3] hydrodynamic plasma expansion during the laser pulse, plasma shielding of the laser radiation and increased heat-conduction loss are possible reasons for the decreasing of the penetration depth. According to our findings the influence of the pulse duration on the penetration depth and threshold fluence is strong. Therefore the effect or effects causing this strong dependency must be strong as well. In what way the effects mentioned in [3] are able to explain the results, is not fully understood and is still subject to be investigated.

4.3 Quality of the ablation

It has to be mentioned that in the case of steel it was very difficult to measure the depth and the area of the crater. Figures 4a) and 4b) show an ablated crater in copper with 256 pulses taken with a Scanning Electron Microscope (SEM) for pulse durations of 10ps and 50ps, respectively. In the case of 10ps pulse duration a smooth crater surface can be seen; in the case of 50ps there is a little melted material inside the crater. Plotting the cross section of the crater revealed an ideal parabolic shape in the case of 10ps, where the depth of the crater could be measured accurately. In the case of 50ps measuring the depth of the crater needed some interpretation. Never the less it still was possible to estimate the depth of the crater accurate enough.

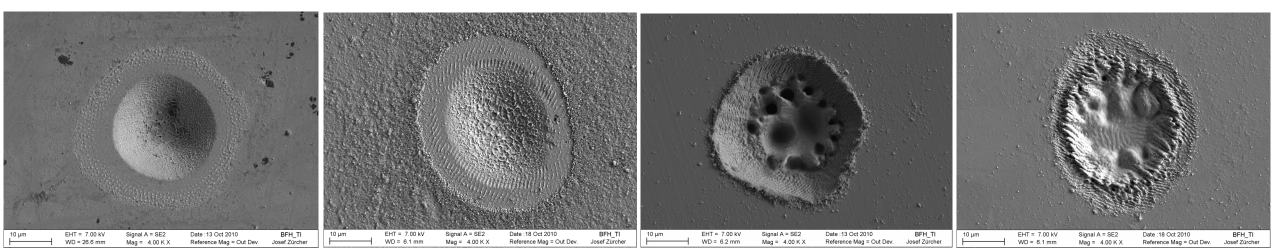
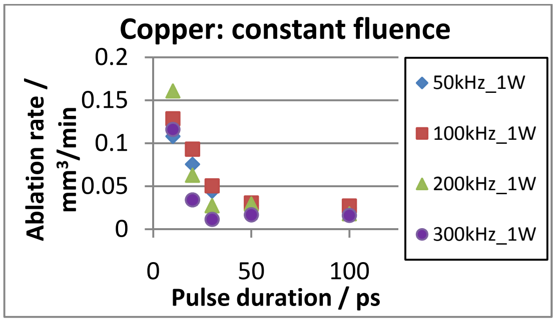


Figure 4a) and 4b): SEM picture of the ablation crater in copper for pulse duration of 10ps and 50ps, respectively. Figure 4c) and 4d): SEM picture of the ablation crater in steel for pulse duration of 10ps and 50ps, respectively.

A different picture is seen in the case of steel: Figures 4c) and 4d) show the ablated crater with 256 pulses in steel for pulse durations of 10ps and 50ps, respectively. In opposite to copper even for pulse duration of 10ps there is a lot of melted material inside the crater. The shape of the cross section of the crater is not parabolic at all and it is difficult to estimate the depth of the crater because of the melted material at the bottom of the crater. The same is true for estimating the area of the crater because the edge of the crater is neither circular nor well defined. Therefore it was very difficult to measure the diameter of the ablated area or the ablation depth, respectively.

4.4 Dependency of volume ablation rate

Next, the dependency of the ablation rate dV_{abl}/dt on the pulse duration has been investigated. Figures 5a) and 5b) show the ablation rate dV_{abl}/dt as a function of the pulse duration at a constant repetition rate f and a constant fluence for copper and steel, respectively. The average power was 1W and the repetition rates were 50kHz (diamond), 100kHz (square), 200kHz (triangle) and 300kHz (dot). In both cases the ablation rate decreases rapidly by a third with increasing pulse duration from 10ps to 50ps. Between 50ps and 100ps pulse duration the volume ablation rate does not change significantly. According to the equation (4) this is a consequence of the strongly increasing threshold fluence and decreasing penetration depth with increasing pulse duration (cf. section 4.2).



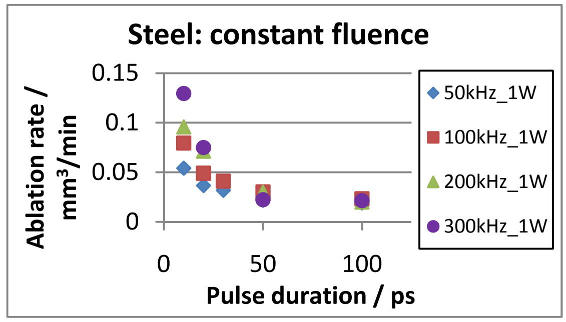
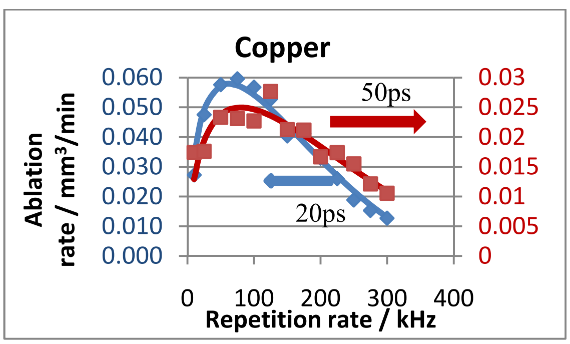


Figure 5a): Volume ablation rate per pulse for copper as a function of the pulse duration, where the fluence and the repetition rate were kept constant. Figure 5b): Volume ablation rate for steel as a function of the pulse duration, where the fluence per pulse and the repetition rate were kept constant.

As it has been indicated in section 2.2 in the case of cold ablation the ablation rate depends on the repetition rate, as well. In order to see if a similar behavior can be seen for pulse durations between 10ps and 100ps, the ablation rate as a function of the repetition rate at a constant average power for copper has been plotted. Figure 6a) clearly shows that the ablation rate behaves in a similar way as predicted with equation (3) for cold ablations. According to the equation (5) and (8), respectively, the optimum repetition rate f_{opt}, where a maximum ablation rate is achieved, depends on the threshold fluence. Because the threshold fluence decreases with increasing pulse duration, the optimum repetition rate f_{opt} increases as well. This relationship could be confirmed with our measurements as well.



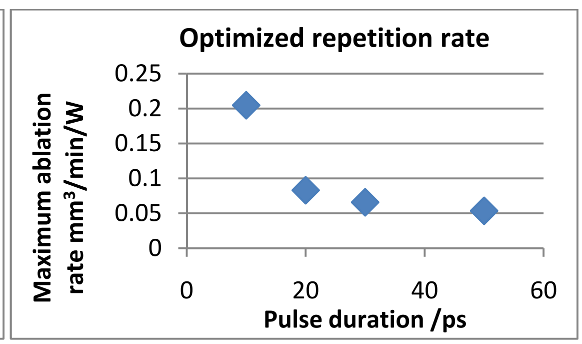


Figure 6a: Volume ablation rate for copper as a function of the repetition rate at a pulse duration of 20ps (diamond) and 50ps (square). The optimum repetition rate is at 60kHz and 90kHz, respectively. Figure 6b: Volume ablation rate for copper as a function of the pulse duration for optimized repetition rate.

Additionally, it is of interest to know the maximum volume ablation rate, which is achieved at the optimum repetition rate according to equation (4), as a function of the pulse duration. Starting with the measured values for the threshold fluence and penetration depth the optimum repetition rate and the maximum volume ablation rate per average power as a function of the pulse duration have been calculated and plotted in figure 6b). As it can be seen the maximum volume ablation rate for copper decreases between 10ps and 50ps, too; a rapid decrease can be observed between 10ps and 20ps pulse duration. A similar behavior is expected with steel.

In the case of copper in the region of 10ps to 50ps our results support the logarithmic behavior of the ablation rate as expressed in equation (1) and (3) up to a fluence per pulse of $2 J/cm^2$. This is in opposite to the findings reported in [3] where the relationship for pulse durations above 20ps is not logarithmic anymore. In the case of steel in the region of

10ps to 50ps the logarithmic behavior only is suitable for low fluence below 0.5 J/cm^2. The ablation quality of steel is very poor. In the center of the ablated crater melted material could be observed which make it difficult to estimate the ablation depth as mentioned above.

5. SUMMARY

In the region of 10ps to 100ps neither copper nor steel is in the regime of cold ablation. In the case of copper the relationship between the ablation depth and volume ablation rate on the fluence is still logarithmic whereas in the case of steel the logarithmic behavior only is true at low fluence. In both cases, copper and steel, the penetration depth, the threshold fluence and ablation rate are depending on the number of pulses and even more on the pulse duration. In the region of 10ps to 50ps a strong dependency is seen; between 50ps and 100ps the dependency is less significant.

Further in the case of copper the quality of the ablation for pulse durations between 10ps and 30ps is good whereas above 30ps more and more melted material in and around the crater is seen. In the case of steel debris in the crater are seen even with shorter pulse durations.

As a consequence of these findings, from the point of view of a maximum volume ablation rate and the quality of the ablation process, shorter pulses will generate the better results. Therefore, independently of the method of generating the laser pulses, systems with pulse durations in the regime of tenth of picoseconds are only in a limited way a good alternative to pulsed laser systems with pulse durations of 10ps and less. In the case of copper acceptable results are expected whereas in the case of steel the results probably will not satisfy all the expectations. Therefore any laser systems with pulse durations of more than 10ps must show economical advantages in order to be competitive with laser systems of 10ps pulse duration or less.

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